NON-ANNULAR, HEMISPHERIC SIGNATURE OF THE WINTER NAO

J. García-Serrano (BSC, Spain / javier.garcia@bsc.es), R.J. Haarsma (KNMI, The Netherlands / rein.haarsma@knmi.nl)

Sensitivity experiments with an atmospheric general circulation model (AGCM) without a proper stratosphere are performed to locally force a North Atlantic Oscillation (NAO)-like response in order to analyse the tropospheric dynamics involved in its hemispheric extent. Results show that the circulation anomalies are not confined to the North Atlantic basin not even within the first ten days of integration, where the atmospheric response propagates downstream into the westerly jets. At this linear stage, transient-eddy activity dominates the emerging, regional NAO-like pattern while zonal-eddy coupling may add on top of the wave energy propagation. Later at the quasi-equilibrium nonlinear stage, the atmospheric response emphasizes a wavenumber-5 structure embedded in the westerly jets, associated with transient-eddy feedback upon the Atlantic and Pacific storm-tracks. This AGCM waveguided structure rightly projects on the observational NAO-related circumglobal pattern, providing evidence of its non-annular character at tropospheric levels. These findings support the view on the importance of the circumglobal waveguide pattern (CWP) on the development of NAO-related anomalies at hemispheric level. It could help to settle a consensus view of the Arctic Oscillation, which has been elusive so far.

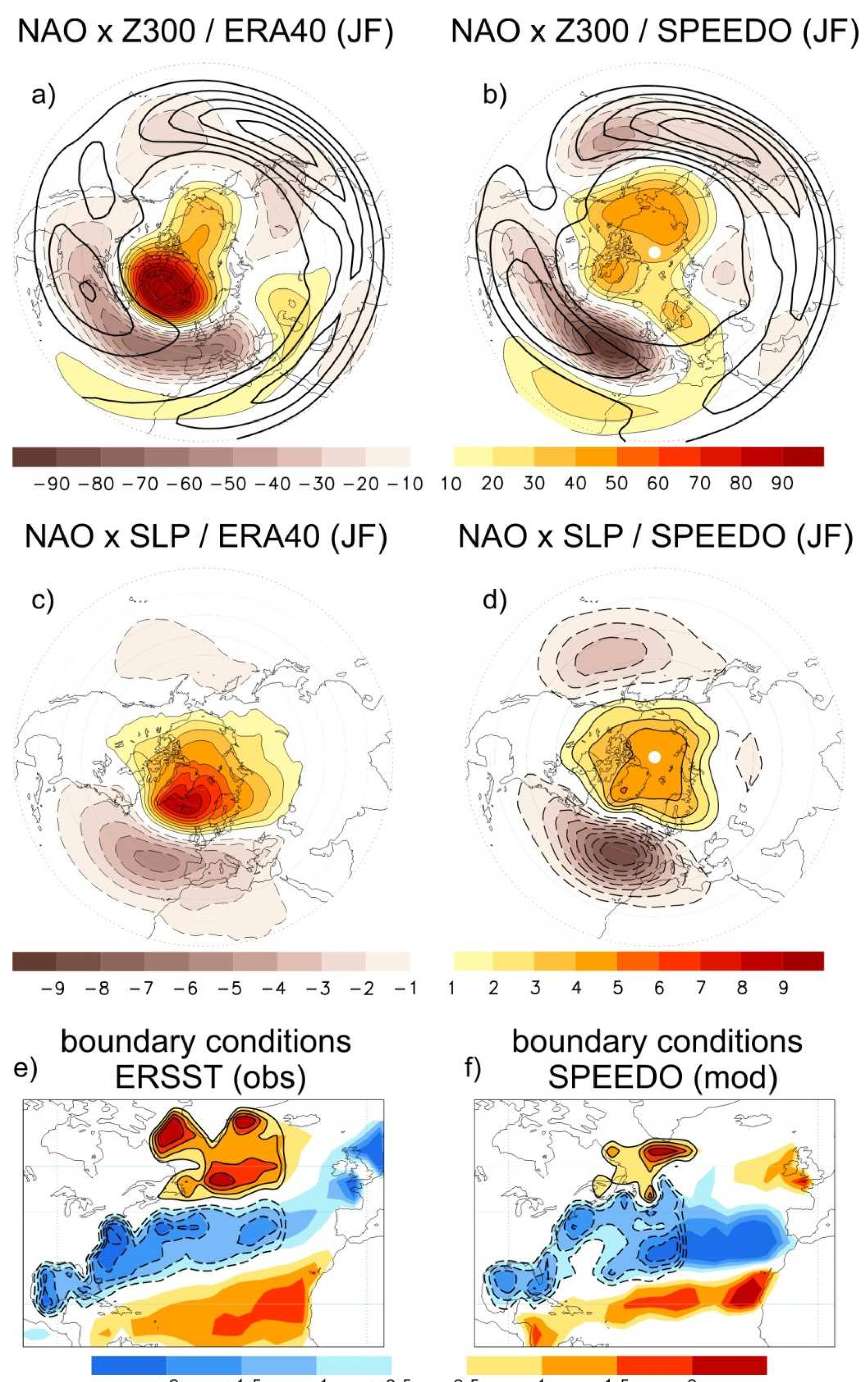


Figure 1: Regression map of ERA40 (a, c) and SPEEDY-MICOM (SPEEDO; b,d) Z300 (m; top) and SLP (hPa; middle) anomalies in January-February onto the corresponding NAO index. Overplotted in top panels is the corresponding climatological zonal wind at 300hPa (ci=10ms^{-1} starting in 20ms^{-1}). Contours in bottom panels delimit the forcing fields (SST anomalies; ºC) of the AGCM runs.

[1] At mid/upper-tropospheric levels, the hemispheric anomalies associated with the observational NAO depicts a characteristic pattern, with two weak centres of action in the North Pacific basin and an elongated one at North Atlantic mid-latitudes projecting on another two. These four apparent centres of action are distributed along the CWP pattern (Branstator 2002) and may, particularly the two over the North Pacific, reflect a stationary Rossby wavetrain triggered from the North Atlantic basin. The waveguide effect of the westerly jets is illustrated here by the collocation of the anomalies within the climatological zonal wind (Fig. 1a, thick contours). The fifth centre of action in the wavenumber-5 structure of the NAO/CWP pattern is located around the Arabian Peninsula, which becomes more noticeable in the streamfunction field.

[2] SPEEDY overestimates the amplitude of the North Pacific centre of action related to the NAO at surface. At the upper troposphere, the regression map of Z300 (Fig. 1b) remains showing an overestimation of the NAO-related anomalies in the central-eastern North Pacific. This feature might be associated with the overestimated local wind maxima (Figs. 1a-b, thick contours) and more vigorous transient-eddy activity there as compared to the North Atlantic (Figs. 4b-c, 5d, thick contours). On the contrary, SPEEDY underestimates the amplitude of the centre of action at high latitudes (Figs. 1b,d). This latter could be linked to the fact that SPEEDY does not have a proper, active stratosphere, in that coupling processes and feedbacks (e.g. Ambaum and Hoskins 2002) are underrepresented.

[3] Beyond biases, SPEEDY rightly captures both the NAO-related quasi-zonally symmetric signature at surface (Fig. 1d) and the wavenumber-5 structure at the upper troposphere (Fig. 1b), which projects on the observational one (Fig. 1a; spatial correlation of 0.73).

[4] <u>The hypothesis is that the hemispheric scale of the NAO is non-annular in origin, namely the NAO/CWP could be at the basis of the AO development, implying that tropospheric dynamics are key for its circumglobal extent</u>.

- The atmosphere model used in this study is the Simplified Parameterizations primitivE-Equation DYnamics (SPEEDY) model. It is an intermediate complexity AGCM based on a spectral primitive equation core and a set of simplified parameterization schemes, which were especially designed to use in models with just a few vertical levels but are similar to those adopted in state-of-the-art AGCMs. SPEEDY has a vertical resolution of seven layers and a triangular spectral truncation at total wavenumber 30 (i.e. T30L7). The levels correspond to 925, 850, 700, 500, 300, 200, and 100 hPa. SPEEDY has a good damping parameterization in the upper-most level that allows absorption of waves and prevents spurious reflection.

- In order to obtain SST forcing fields for the AGCM sensitivity experiments, a coupled run is firstly analysed. The coupled model SPEEDO (SPEEDY-Ocean) was configured for the Atlantic basin from 45ºS to 60ºN, with restoring conditions of the thermodynamic properties applied at the northern and southern boundaries; outside the Atlantic and over land climatological surface temperature was prescribed. The ocean component consisted of the Miami Isopycnic Coordinate Ocean Model (MICOM) version 2.7 (Bleck et al. 1992). SPEEDO was integrated for 60 years from which the last 50 years are used for analysis (Haarsma et al. 2005).

- A set of sensitivity experiments with SPEEDY have been performed, namely control (CTL) and perturbed runs, both consisting of 200-member ensembles of 30-day integrations for the month of January. The initial conditions for the first of January were obtained from a 200-year integration with climatological SSTs. The CTL transient simulations use SST climatology as boundary condition. In the perturbed transient simulations, a SST anomaly pattern is prescribed in the North Atlantic with climatology elsewhere (Fig. 1e,f).

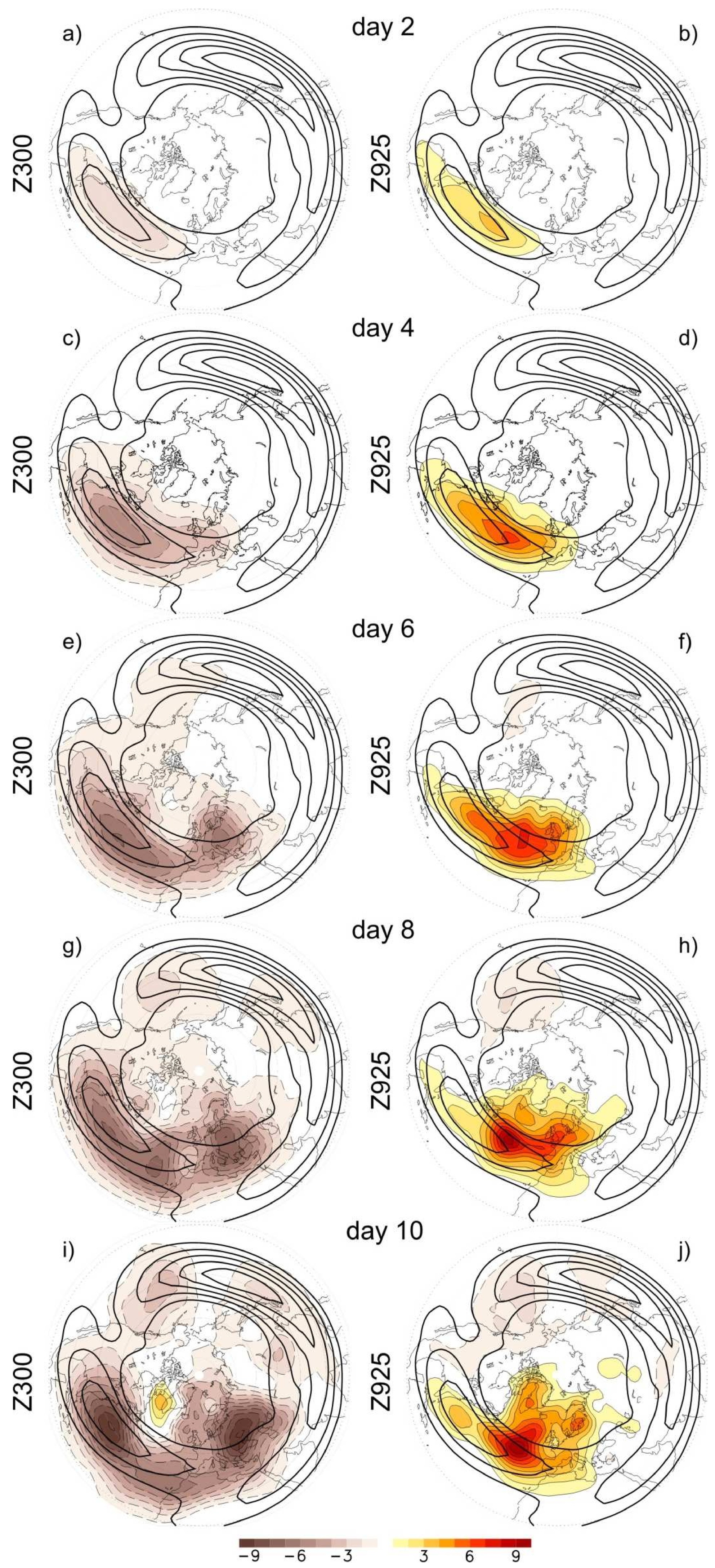


Figure 2: [shading/thin contours] Ensemble-mean response for geopotential height at 300hPa (Z300, m; left) and 925hPa (Z925, m; right) every two days of integration. [thick contours] Overplotted is the ensemble-mean monthly-mean zonal wind at 300hPa (ci=10ms^{-1} starting in 20ms^{-1}) from the control run.

[5] The ensemble-mean response at day 2 of integration covers the whole Atlantic basin, from the Gulf of Mexico to offshore Iberian Peninsula (Figs. 2a,b).

[6] At day 4, the circulation anomalies penetrate into Europe, with the upper-tropospheric anomalies (Fig. 2c) going slightly ahead than the lower-tropospheric anomalies (Fig. 2d).

[7] When the atmospheric anomalies are well developed over Europe at day 6 of integration, particularly for Z300 (Fig. 2e), the ensemble-mean response shows a barotropic anomaly at the exit-region of the North Pacific jet (Figs. 2e,f). This is striking, as no clear geopotential height anomalies propagating downstream, thus connecting the two regions, have been shown.

[8] Latitudinal shifts of the westerly jets may make the zonally-oriented Rossby waves undistinguishable; hence, an analysis is performed by subtracting the zonal-mean in the ensemble-mean response for Z300 (Fig. 3-left). It is shown that the zonally-asymmetric circulation anomalies effectively propagate downstream into the westerly jets, thereby discarding that Rossby wave energy propagates upstream to the North Pacific. Wave activity flux diagnostic confirms that the energy propagation is eastward, off the North Atlantic jet (not shown).

[9] Fig. 3a-right summarizes how the wave perturbation at 40ºN propagates downstream and amplifies with integration time; and Fig. 3b-right shows that the propagating zonally-asymmetric circulation anomalies are not an artefact of the residual operator.

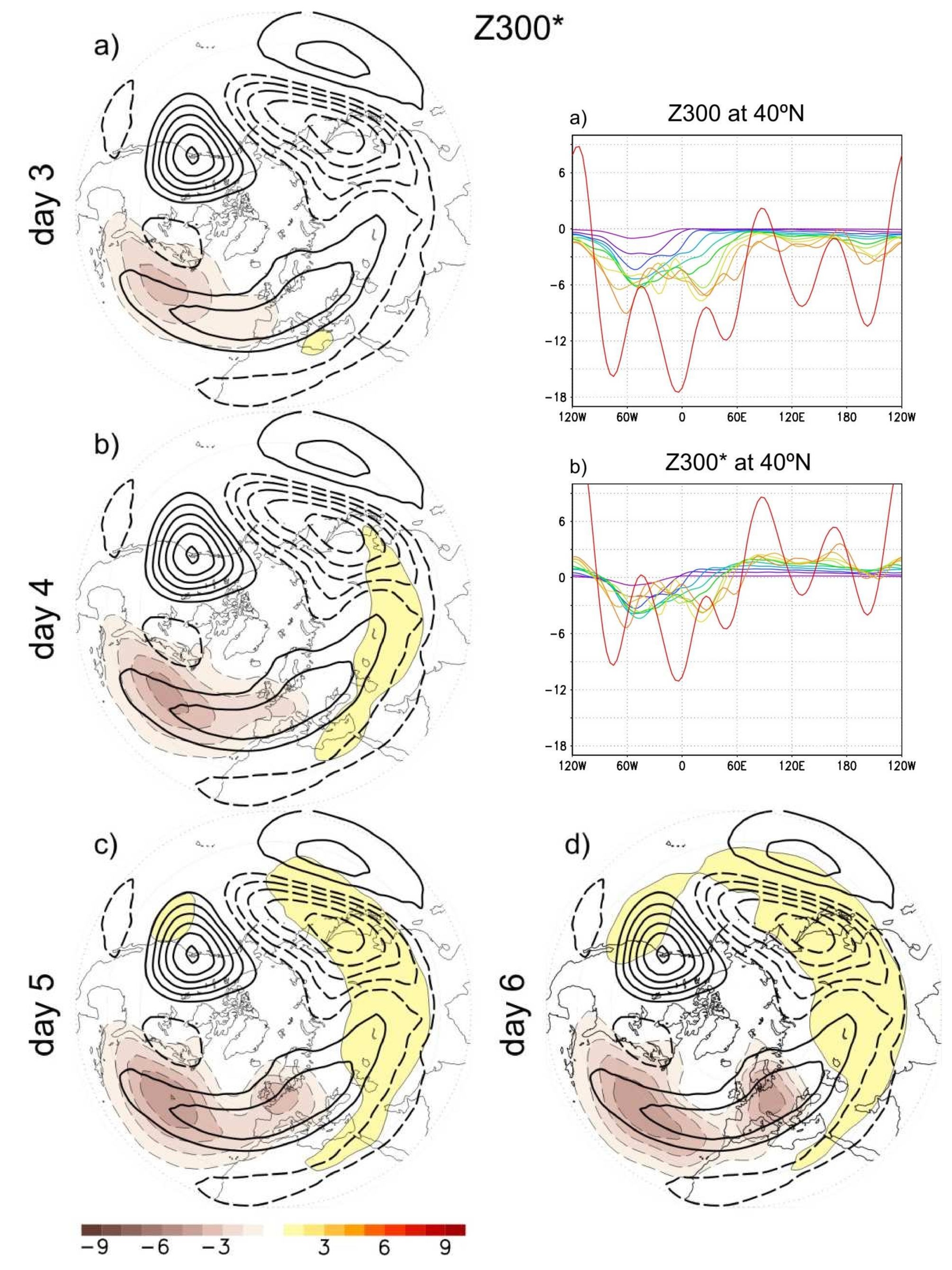
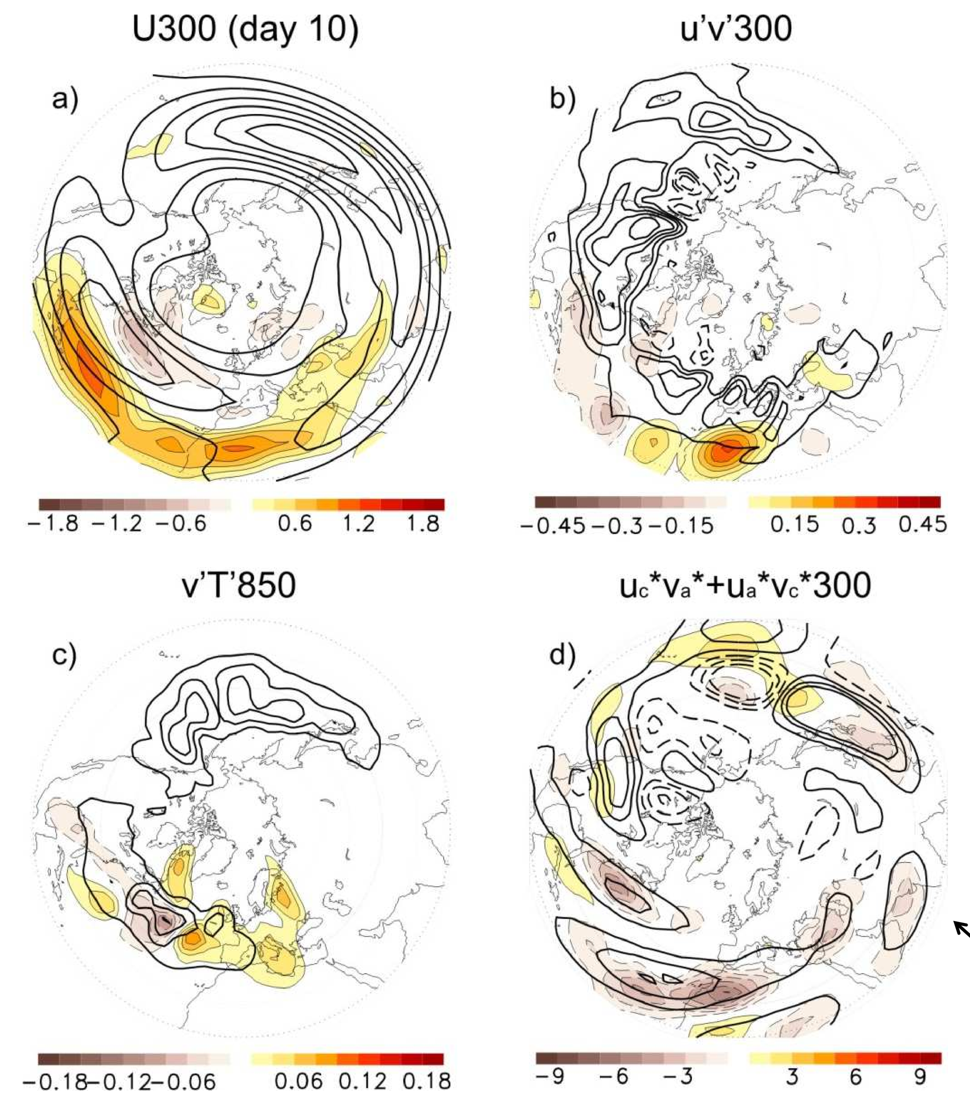
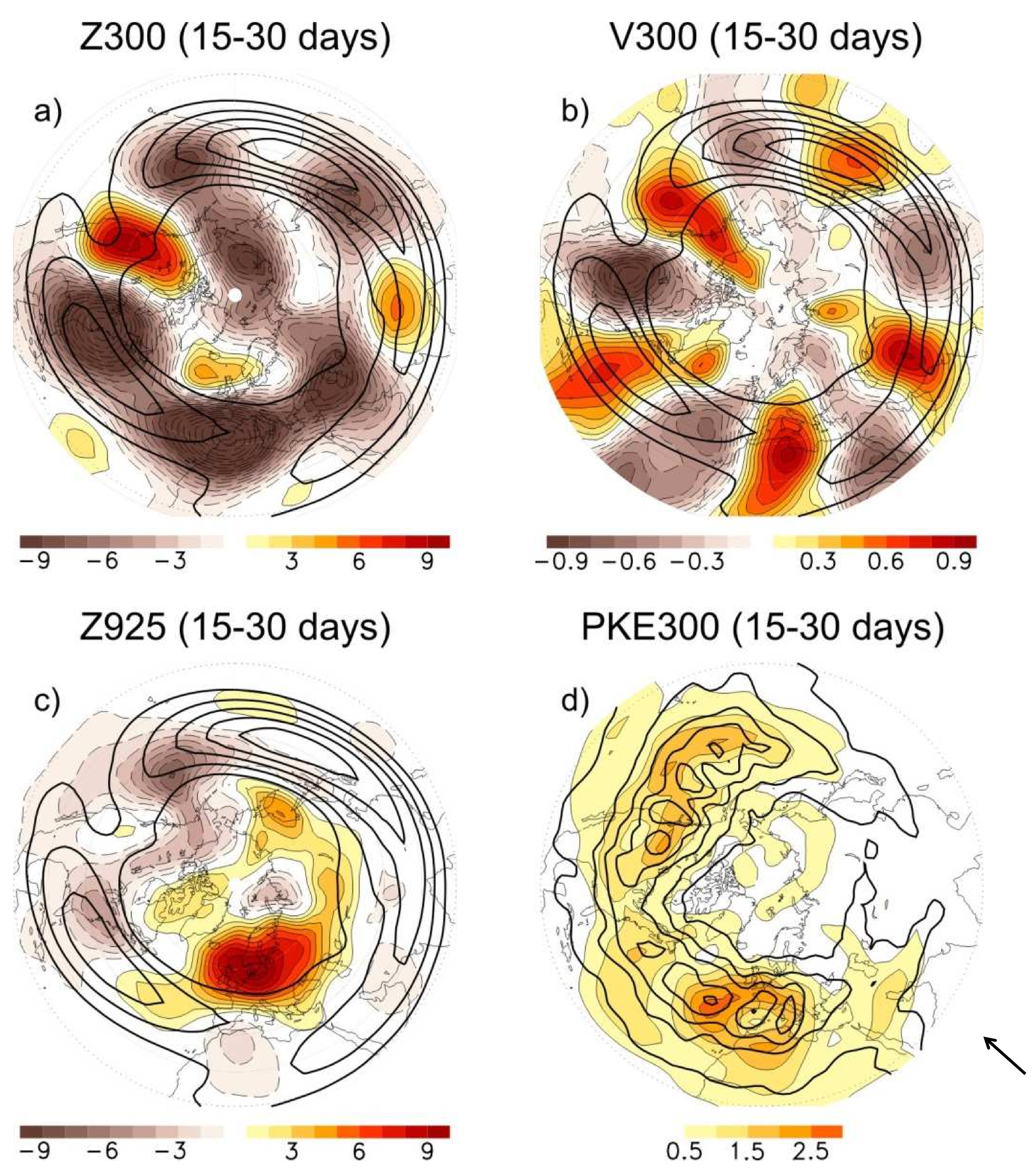


Figure 3: [shading/thin contours] Ensemble-mean response for the asymmetric part, i.e. departure from zonal-mean, of geopotential height at 300hPa (Z300*, m; left) at days 3-to-6 of integration. [thick contours] Overplotted is the ensemble-mean monthly-mean Z300* (ci=50m) from the control run. (top-right) Ensemble-mean response for geopotential height at 300hPa (Z300, m; a) and its asymmetric part (Z300*, m; b) at 40ºN every day of integration from 1 (purple) to 10 (orange), plus the averaged over the days 15-30 (red).



[10] At day 10, the ensemble-mean response yields positive circulation anomalies at high latitudes of the North Atlantic, pointing out the first hint of a barotropic NAO-like pattern (Figs. 2i,j). The emerging barotropic structure is accompanied by a southward displacement of the eddy-driven jet (Fig. 4a), consistent with the settling of the negative NAO phase. Transient-eddy activity is in agreement with this latitudinal shift (Figs. 4b,c). Zonal-eddy coupling could contribute, against dissipation, to the remote atmospheric response (Figs. 3-left, 4d).

Figure 4: [shading/thin contours] Ensemble-mean response at day 10 of integration for zonal wind at 300hPa (U300, ms^{-1}; a), transient-eddy momentum flux at 300hPa (u'v'300, m^{2}s^{-2}; b), transient-eddy heat flux at 850hPa (v'T'850, ms^{-1}K; c), and zonal-eddy momentum flux at 300hPa ($u_c^*v_a^*+u_a^*v_c^*$300, m^{2}s^{-2}; d); the latter computed from the climatological stationary wave (u_c^*, v_c^*) and daily anomalous zonal-eddy components (u_a^*, v_a^*). All eddy covariances have been averaged over the days 8-10 of integration. [thick contours] Overplotted in each panel is the ensemble-mean monthly-mean of the corresponding field from the control run: U300 (ci=10ms^{-1} starting in 20ms^{-1}; a), u'v'300 (ci=5m^{2}s^{-2}; b), v'T'850 (ci=2.5ms^{-1}K; c), and $u_c^*v_c^*$300 (at ±20, ±60, ±100m^{2}s^{-2}; d); with u'v'300 and v'T'850 computed from filtered daily data using the 24h-difference filter (e.g. Wallace et al. 1988; Chang and Fu 2002).



[11] At day 8 of integration (Figs. 2g,h), two centres of action over the North Pacific basin are noticeable in the ensemble-mean response at the upper troposphere. The barotropic centre of action at the exit-region of the North Pacific jet has increased in amplitude (cf. Figs. 2e,f), indicating that it is not only sustained against dissipation but amplified by likely extracting energy from the mean-flow on top of the wave energy propagation.

[12] Two days after it keeps growing (Figs. 2i,j). The wavenumber-5 structure of the ensemble-mean response for Z300 embedded in the westerly jets at day 10 of integration (Fig. 2i) is already reminiscent of the quasi-equilibrium response (Fig. 5a) and projects on the simulated NAO/CWP pattern (Fig. 1b; spatial correlation of 0.41).

[13] At the quasi-equilibrium stage the circumglobal response is fully established (Fig. 5a; spatial correlation with Fig. 1b of 0.59). The wavenumber-5 structure is better illustrated by the meridional component of the wind (Fig. 5b). The waveguided circulation yields a deep barotropic anomaly at the exit-region of the North Pacific jet (Fig. 5c); which is collocated with a relative maximum of the perturbation kinetic energy (Fig. 5d)). The response over the North Atlantic (Fig. 5c) does not entirely resemble the model NAO pattern (Fig. 1d) because of the shortness of the integration, but transient-eddy feedback has been efficient enough to start setting the barotropic dipole-like pattern (cf. Figs. 2i,j).

Figure 5: [shading/thin contours] Ensemble-mean response averaged over the days 15-30 of integration for geopotential height at 300hPa (Z300, m; a), meridional wind at 300hPa (V300, ms^{-1}; b), geopotential height at 925hPa (Z925, m; c), and perturbation kinetic energy at 300hPa (PKE300=(u'u'+v'v')/2, m^{2}s^{-2}; d); the eddy covariances have been averaged over the days 15-30 of integration. [thick contours] Overplotted is the ensemble-mean monthly-mean zonal wind at 300hPa (ci=10ms^{-1} starting in 20ms^{-1}; a-c) and PKE300 (ci=45m^{2}s^{-2}; d) from the control run; the latter computed from filtered daily data using the 24h-difference filter (e.g. Wallace et al. 1988; Chang and Fu 2002).

The temporal development of the NAO-related circumglobal response to extratropical North Atlantic SSTs, with the transition from a linear Rossby wave response towards a nonlinear response including transient-eddy feedbacks, has been investigated with SPEEDY-AGCM simulations under perpetual January conditions.

- The results shown here support the hypothesis that the hemispheric signature of the winter NAO at surface, particularly the associated circulation anomalies over the North Pacific basin, could be explained by tropospheric dynamics (without the need of interaction with the stratosphere) involving a Rossby wavetrain channelized into the westerly jets, which is consistent with the CWP pattern at the upper troposphere (e.g. García-Serrano et al. 2011). The resemblance of this waveguided, non-annular teleconnection to the observational and model NAO-related upper-tropospheric wavenumber-5 structure suggests that NAO/CWP-like variability represents a natural mode of atmospheric variability (Branstator 2002).
- The findings also imply that the mid-latitude North Pacific and North Atlantic centres of action in the hemispheric NAO signature do not fluctuate in phase, in agreement with the idea that no longitudinal coherence in transient-eddy activity is expected (e.g. Vallis and Gerber 2008; Gerber and Vallis 2009; Wettstein and Wallace 2010); thereby, the NAO/CWP paradigm is in contrast with the AO/NAM paradigm, where a large-scale, hemispheric seesaw between middle and high latitudes is postulated. However, the NAO/CWP-like variability does not revoke the AO/NAM pattern, but instead provides a dynamical framework to consistently understand its quasi-zonally symmetric appearance at surface. From this perspective, the AO would correspond to the circumglobal extension of the more regional NAO. The NAO/CWP could also explain why the mode of variability in the Northern Hemisphere appears to be dominated by atmospheric variability in the Atlantic sector (e.g. Thompson et al 2003). It could well help to settle a unifying view of the NAO-AO variability, which is much-needed due to its important environmental impacts and implication for climate forecasting.

Targeted modelling efforts are required to provide further support to the dynamical framework discussed here. Exploration could point at analysing the downstream propagation of NAO-related atmospheric anomalies induced by tropospheric mean-flow instabilities (e.g. Watanabe 2009) and/or changes in the stratospheric polar vortex strength (e.g. Garfinkel et al. 2013). Theoretical understanding of the predominance of wavenumber-5 in the CWP might also be subject of research.